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LOCATIONS OF SMALL EARTHQUAKES NEAR THE TRIFURCATION OF THE SAN JACINTO FAULT SOUTHEAST OF ANZA, CALIFORNIA

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ABSTRACT

About 100 small earthquakes ($M \approx \frac{1}{2}$ to 2) which occurred near the trifurcation of the San Jacinto fault southeast of Anza, California, have been accurately located using five- and six-station arrays with dimensions of about 10 km. The pattern of epicenters is complex and extends several km outside of the area outlined by the traces of faulting. Patterns of seismicity observed on opposite sides of the San Jacinto fault are significantly different. On the southwest side, a concentration of foci lies at a depth of about 4–7 km along the projected extension of the Coyote Creek fault a few km northwest of the last surface evidence of faulting. On the northeast side, earthquakes are concentrated at depths between 10 and 15 km. A group of the latter events recorded about 1 week after the magnitude 4.7 earthquake of May 21, 1967 forms a linear pattern parallel to the San Jacinto fault with depths from 3 to 15 km. This pattern may represent the zone of energy release or slip for that earthquake and possibly the plane of the San Jacinto fault at depth, although the epicenters are located about 2 to 3 km to the northeast of the trace of the San Jacinto fault. Most of the earthquakes located in this study are not aftershocks in the usual sense, i.e., easily correlated with a preceding large earthquake. They represent a complex pattern of seismicity which has continued at least for the last 3 years on the micro-earthquake level and for the last 30 years on the macroseismic level.

Introduction

The San Jacinto fault is the most active fault in Southern California—both in terms of historic large earthquakes (Allen *et al.*, 1965) and present day micro-earthquake activity (Brune and Allen, 1967). The section of the fault studied here has had a continuous high rate of microearthquake activity for the last few years. In this area the San Jacinto fault trifurcates (see Figure 1), and southeast of the trifurcation the name San Jacinto fault was applied by Sharp (1967) to the branch with the most continuous recent scarps and the largest net displacement. On the other hand the Coyote Creek branch of the fault is more nearly aligned with the regional trend of the San Jacinto fault to the northwest, and continuing strain along the Coyote Creek branch is indicated by the magnitude 6.5 Borrego Mountain earthquake of April 9, 1968, which was associated with a 35 km surface break starting 50 km southeast of Anza (Allen *et al.*, 1968b). The Buck Ridge branch of the fault is not a major one and dies out within the area of Figure 1.

The magnitude 6.0 "Terwilliger Valley" earthquake of March 25, 1937 (Wood, 1937) was centered directly in the area of this study. Several other earthquakes with magnitudes greater than 6.0 have occurred a few tens of km northwest and southeast of this area in historic times. Subsequent to 1937 no earthquake of magnitude 5 or greater has occurred within the limits of Figure 1; however, more than a dozen magnitude 4 events and numerous smaller earthquakes have been located there by the Caltech Seismological Laboratory using the southern California seismograph net (see, for example: Allen 1967, Allen *et al.*, 1968a). Locations for these earthquakes have been assigned accuracies of either ±5 km or ±15 km and are broadly distributed over the zone of trifurcation of the San Jacinto fault. The rate of slip along the San Jacinto fault corresponding to the sum of moments of historic earthquakes is 1.2 cm/year (Brune, 1968).

The geological investigations of Sharp (1967) indicate that: (1) cumulative right

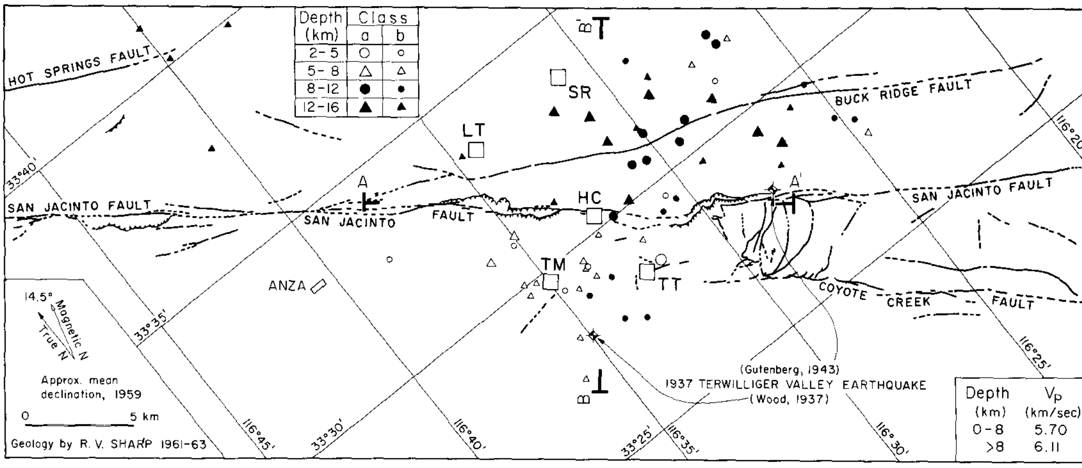

FIG. 1. Map of the zone of trifurcation of the San Jacinto fault southeast of Anza, California with earthquake locations from Array #1 (1966). The seismic stations are indicated by large open squares.

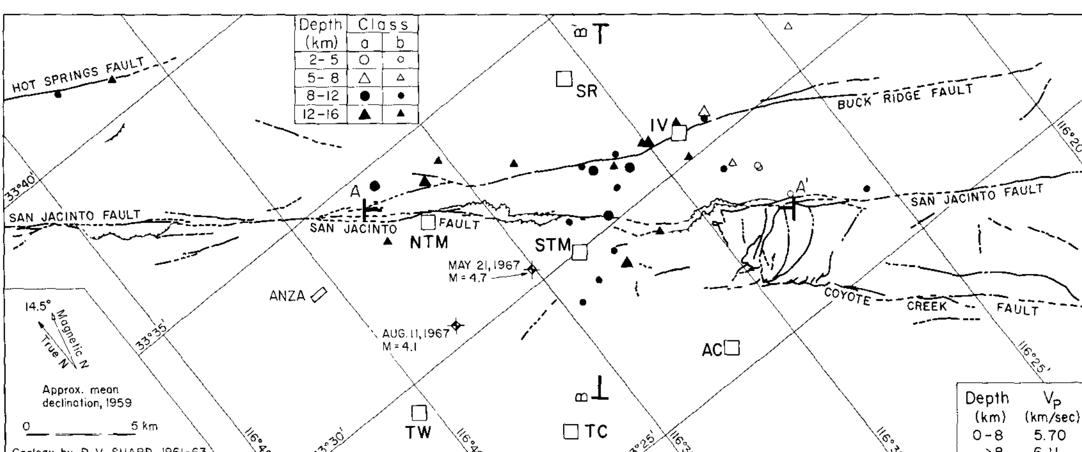

FIG. 2. Map of the zone of trifurcation of the San Jacinto fault southeast of Anza, California with earthquake locations from Arrays #2 and #3 (1967). The seismic stations are indicated by large open squares. For two larger earthquakes located using the Caltech Southern California Array, the magnitudes and dates are shown next to the epicentral symbols.

lateral displacement across the San Jacinto fault zone is at least 15 miles (24.1 km); Pleistocene gravels are offset at least 3.2 miles (5.2) km and stream courses have been displaced as much as $\frac{1}{2}$ mile (0.8 km); (3) the southwestern side of the fault zone has been relatively raised through a probable 1 to 2 mile (1.6 to 3.2 km) vertical component of net displacement.

One of the important aspects of our data is that a large number of the small earthquakes which were accurately located are not aftershocks in the ordinary sense. The original purpose of our field program was to monitor micro-earthquake activity in an area where no large earthquake had recently occurred but where preliminary surveying indicated a high level of activity. Other recent studies of small earthquakes in California have been studies of aftershock sequences of moderately large earthquakes. In some of these cases foci were closely concentrated along simple fault planes (Eaton, 1968), and in other cases they were concentrated in a small volume with dimensions of the order of a few to several km (McEvilly, 1966; 1967). In still other cases foci were distributed in a complicated fashion over broad areas tens of km in dimensions (Udias, 1965). The pattern of seismicity found in this study is complex and is similar to a pattern found near Cajon Pass (Brune and Allen, 1967).

TABLE 1

Trailer Operation Data for Anza Arrays, 1966, 1967

Site Name	Trailer No.	Lat. N.	Long. W.	Elev. (ft)	Approximate Dates of Operation
Horse Canyon (HC)	4	33°30.4′	116°32.7′	3120	Array ✱1, Horse Canyon, Turkey Track, Santa Rosa Mt., Lookout Mt., Table Mt.; April 26, 1966 to May 17, 1966 (Figure 1)
Turkey Track (TT)	5	33°28.4′	116°32.5′	2710	
Santa Rosa Mt. (SR)	6	33°33.6′	116°31.0′	5110	
Lookout Mt. (LT)	8	33°33.5′	116°34.3′	5040	
Table Mt. (TM)	1	33°39.7′	116°35.0′	3920	
Adler Canyon (AC)	8	33°25.7′	116°31.8′	2450	Array ✱2, Adler Canyon, Tule Canyon, Indian Village, Santa Rosa Mt. ✱2, North Table Mt.; May 24, 1967 to May 31, 1967 (Figure 2)
Terwilliger (TW)	5	33°29.4′	116°40.4′	4500	
Tule Canyon (TC)	6	33°26.6′	116°37.2′	4080	
Table Mt. South (STM)	7	33°30.0′	116°33.6′	4200	
Indian Village (IV)	4	33°30.7′	116°29.0′	5500	
Santa Rosa Mt. ✱2 (SR)	2	33°33.6′	116°30.8′	4950	
North Table Mt. (NTM)	3	33°33.0′	116°36.7′	4500	Array ✱3, Adler Canyon, Terwilliger, Table Mt. South, Indian Village, Santa Rosa Mt. ✱2, Tule Canyon; June 13, 1967 to June 20, 1967 (Figure 2)

Field Procedure

Earthquakes were recorded on 70 mm film using 5 and 6 trailers of the Caltech portable seismograph array. These systems are described by Lehner and Press (1966). Only vertical-component seismometers were used. The response curve corresponds to curve B in Figure 1 of Brune and Allen (1967) and has a peak at about 20 Hz.

During three different time periods the trailers were distributed in arrays covering the trifurcation of the San Jacinto fault. During each period of operation the distribution of trailers was slightly different (see Figures 1 and 2, and Table 1). An array was first operated for 3 weeks during the summer of 1966. Later, one was operated for 1 week from May 24 to May 31, 1967, following the earthquake centered in the area on May 21, 1967 ($M = 4.7$). An array was again operated for 1 week from June 13 to June 20, 1967, 3 weeks after the earthquake cited above. Figure 5 illustrates several recordings of earthquakes located in this study.

Hypocentral Location

The arrival times of both P and S waves were read and used in a half-space least-squares hypocentral location program similar to that used by Flinn (1960). Events were selected for which at least 4 P-wave times and 2 S-wave times could be read. After trying a range of velocities, we assumed a P velocity of 6.11 km/sec for events with depths greater than 8.0 km and a P velocity of 5.70 km/sec for those with depths less than this. A corresponding S velocity was derived by assuming Poisson's ratio equal to 0.25. The accuracy of reading wave arrivals was ± 0.1 sec for P waves and about ± 0.2 sec for S waves, although identifying the S-wave arrival was sometimes difficult. Standard errors were computed by a location program written by J. Nordquist for the Bendix G-15D in use at the Caltech Seismological Laboratory. A random group of the earthquakes was chosen and also run in this program using a structure with a P velocity of 5.70 km/sec to a depth of 1.0 km and 6.11 km/sec below that depth as a check on the locations. The differences in the results were within the standard errors computed.

Crystalline bedrock of a relatively uniform nature (mainly tonalites and gneisses) underlies the entire region on both sides of the San Jacinto fault and there is little sedimentary cover. All stations were on bedrock; therefore it is unlikely that any significant regional variation of travel time exists within the small array.

The uncertainty in hypocentral locations for events within or very close to the array is estimated to be about ± 2 km in any direction, but considerably larger for events outside the array. A calibration explosion in the center of the array (see Figure 1) was located with an error of 1.2 km in position and 2 km in depth. Various tests were made with reasonable layered-earth models to verify that the assumption of uniform half-space models was not introducing important errors.

Control within a circle 10 km in radius from the center of the array is judged to be good, and the following criteria, based on computer residuals, were adopted to standardize the quality of the earthquake locations plotted in Figures 1 and 2.

Class (a): Locations having all (4 to 6) P-residuals <0.1 sec, all (2 or more) S-residuals <0.2 sec, and standard errors <1 km. These represent the best locations.

Class (b): Locations allowing 2 (of 4 or more) P-residuals >0.1 sec but <0.2 sec, allowing 2 S-residuals >0.2 sec but <0.5 sec, and standard errors <2 km.

Outside of the 10 km circle all of the locations are plotted as class (b) even though they satisfy other requirements for good control. Solutions were found for essentially all the events for which clear arrivals were recorded at 4 stations and for which the S-P times were less than 2 sec (i.e., events within or very close to the array). Most of the events were in the magnitude range $\frac{1}{2}$ to 2.

Pattern of Foci

About two-thirds of the located earthquakes were recorded during the operation of Array #1 in 1966 (see Table 1). The other events were recorded by Arrays #2 and #3 in 1967 subsequent to a magnitude 4.7 earthquake on May 21 and prior to a magnitude 4.1 shock on August 11. The locations of these two larger events, taken from the Caltech Seismological Bulletin, are plotted in Figure 2. (The uncertainty in their location is considerably greater than for events located by our San Jacinto fault arrays.)

The 1966 activity does not simply represent aftershock activity of a large earthquake although it might conceivably be related to the magnitude 6.0 "Terwilliger Valley" earthquake of March 25, 1937 (see Figure 1) or even earlier earthquakes. Prior to Array #1, the latest earthquake located near the array by the Caltech Seismological Laboratory was a magnitude 3.3 event on December 26, 1965. A magnitude 4.0 earthquake did occur on January 7, 1966 and another (M = 4.0) on March 16, 1966 but both were located nearly 30 km to the southeast of Array #1 beyond the limits of Figure 1. In order to eliminate confusion between the 1966 data and the 1967 data which is more definitely related to a preceding magnitude 4.7 earthquake, we have plotted the former in Figure 1 and the latter in Figure 2. The significance of the recording periods should be kept in mind as patterns of foci are discussed.

The earthquake locations given in Figure 1 indicate a complicated pattern of seismicity as might be expected in a zone of complex faulting. The overall zone of earthquakes does not align with the direction of faulting and the earthquake activity is not distributed uniformly over the zone. There are clusters with gaps in between. This may be partly due to our limited recording time.

Southwest of the San Jacinto fault, epicenters are concentrated in a zone along the projection of the Coyote Creek fault about 3 km northwest of the last trace of surface

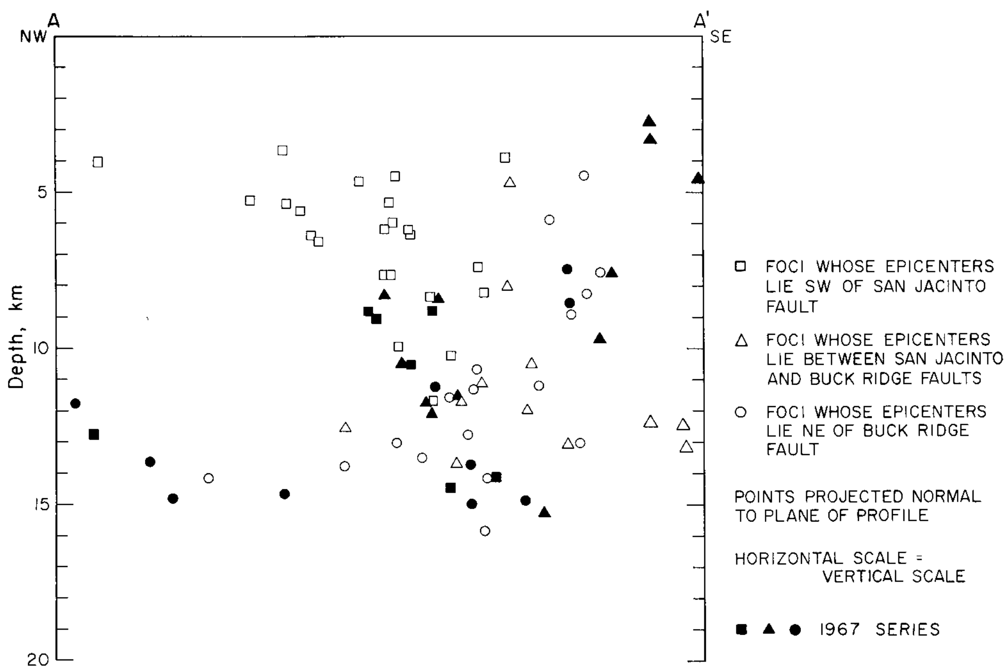

FIG. 3. Longitudinal profile along lines A—A′ of Figures 1 and 2. Good hypocentral control required for plotted foci.

faulting and have associated depths shallower than 8 km. R. V. Sharp (personal communication) states that he has searched that area with care for any suggestion of surface faulting and has found none. Even though active faulting is apparently occurring there at depth, there is no surface evidence directly above.

On the northeast side of the San Jacinto fault most of the foci are deeper than 8 km and show a concentration at a depth between 10 and 15 km in a zone centered below the surface trace of the Buck Ridge fault but extending laterally several km; in particular, extending southwest to the San Jacinto fault.

The pattern of earthquake locations in Figure 2 is not markedly different from that of Figure 1. We again see activity along the projection of the Coyote Creek fault, although on the average these locations are slightly deeper than the 1966 locations. Foci on the northeast side of the fault are again generally deeper than about 8 km. They do, however, show a stronger alignment with the general direction of faulting than those of Figure 1.

The data of Figures 1 and 2 have been combined to construct the cross-section plots shown in Figures 3 and 4. Only locations within the 10-km circle mentioned earlier were used. Cross section A–A′ projects the foci onto the plane of the main break of the San Jacinto fault, which is assumed to be vertical. Foci whose epicenters lie southwest of the fault are indicated by squares, those to the northeast by either triangles or circles as explained in the figure. Note that the cross-section symbols differ from those of the maps. The open symbols indicate foci from 1966; the solid symbols those from 1967.

In Figure 3 the foci southwest of the San Jacinto fault (squares) are limited by a boundary which plunges from a shallow depth to about 12 km depth to the southeast.

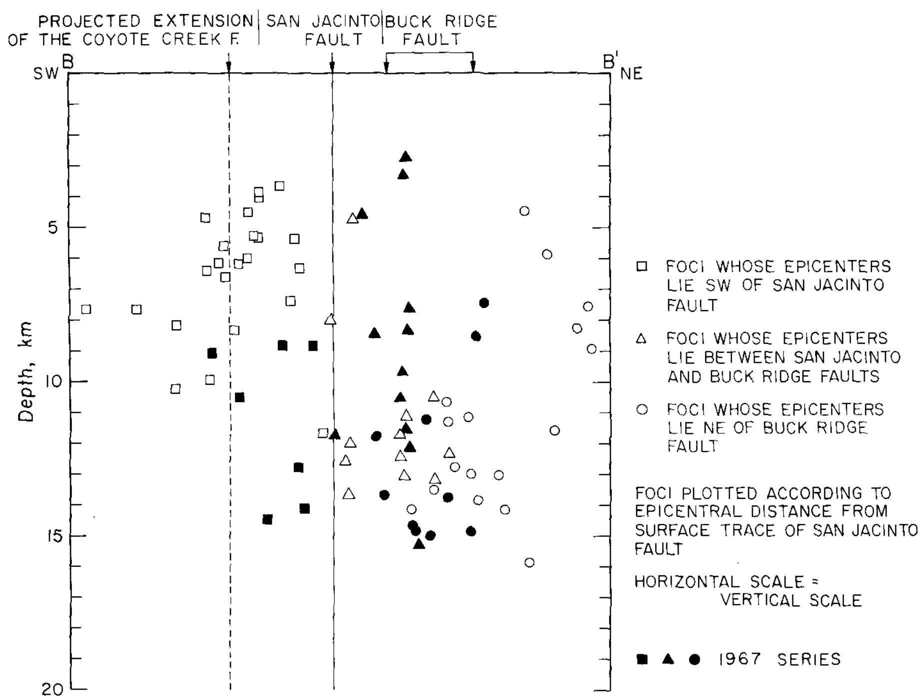

FIG. 4. Transverse profile along lines B—B′ of Figures 1 and 2. Good hypocentral control required for plotted foci.

Most of these events belong to the cluster of shocks along the projection of the Coyote Creek fault. Both the 1966 and 1967 foci appear to be consistent although the latter are generally deeper. The new foci southwest of the San Jacinto fault which are deeper than 12 km appear more closely related to events on the other side of the fault, as will be seen in Figure 4. Indeed, a steep southwesterly dip of the San Jacinto fault would reasonably place these events on the other side.

More than two-thirds of the foci on the northeast side of the San Jacinto fault (triangles and circles, Figure 3) are concentrated between 10 and 15 km. Foci shallower than 10 km occur primarily on the southeastern half of the cross section; in map view their epicenters are broadly spread. Cross section A–A′ indicates significant differences between the patterns of seismicity on opposite sides of the San Jacinto fault during all recording intervals.

Figure 4 shows a section (B–B′) more or less perpendicular to the San Jacinto fault. Foci were projected according to their epicentral distance from the surface trace of the main break of the San Jacinto fault. The fault is arbitrarily plotted as a vertical line. Since the Buck Ridge fault is not parallel to the San Jacinto fault, it projects as a zone which approximately bounds the triangles. As noted earlier, there is no surface indication of the Coyote Creek fault in the zone where many earthquakes occur, but its pro-

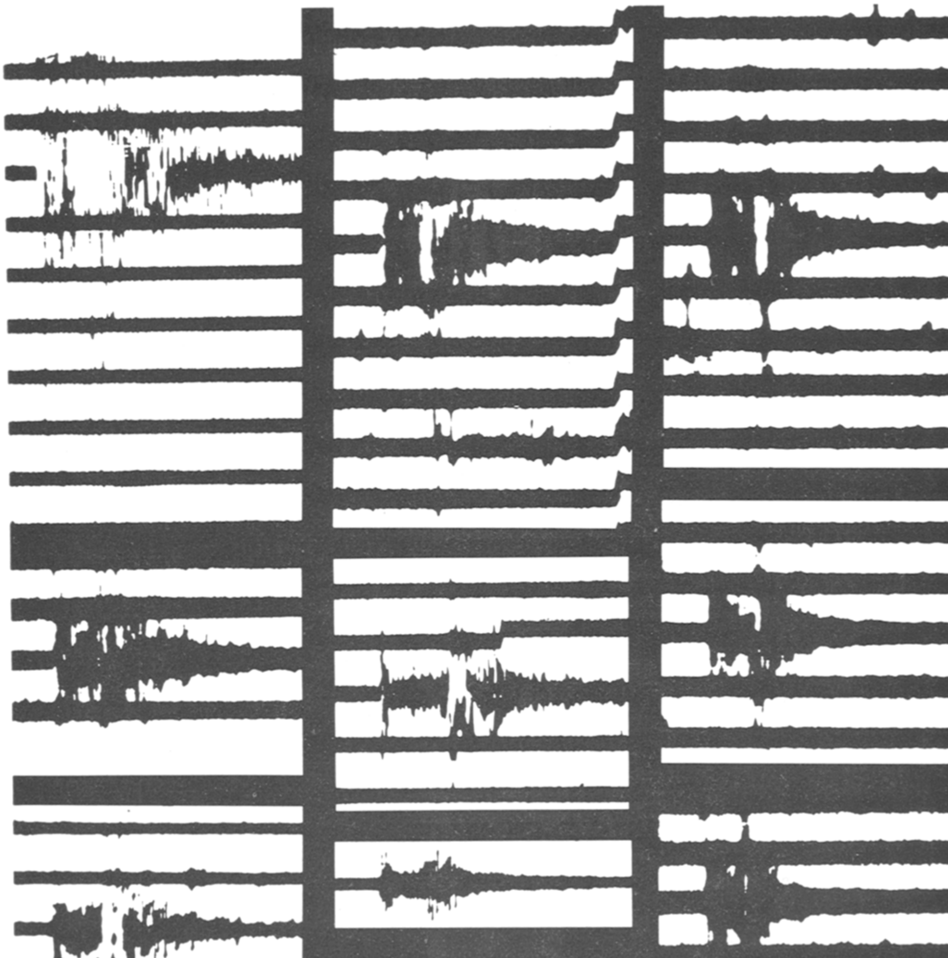

FIG. 5. Sample seismograms of earthquakes located in this study.

jected extension passes through the cluster of shallow events southwest of the San Jacinto fault.

To the northeast of the San Jacinto fault the circles and triangles illustrate a remarkably different pattern of seismicity. The wide zone of activity between 10 and 15 km contrasts with the shallower cluster of activity on the southwest side. Another striking feature is the stronger vertical alignment of the 1967 foci. Inasmuch as the 1967 activity was recorded after a magnitude 4.7 earthquake, it is interesting to speculate whether these foci might be associated with a zone of slippage along either the San Jacinto or Buck Ridge faults, or perhaps associated with a strained volume between the two faults. This issue is elaborated below in the discussion.

First Motion Studies

Although the array was not specifically set up for first motion studies and first motions were often difficult to read, a special study of 15 clearly recorded events was made to determine if there was any systematic pattern but none was found. The most that can be said is that the first motions indicate a complex stress pattern. Only a small fraction of the 15 events had first motions compatible with strike-slip motion along the major faults. Furthermore no simple thrusting model could explain the majority of the events. A greater number of events more closely spaced, both areally and in depth, would have to be studied to yield further conclusions.

Discussion

This study differs from other recent studies in that most of the earthquakes do not represent, in the ordinary sense, aftershocks of a larger earthquake. Although the pattern of 1966 activity might be related to the 1937 "Terwilliger Valley" earthquake ($M = 6.0$) or even earlier earthquakes, it is probable that the activity is more a reflection of the persistent high seismicity of this area for the last 30 years.

The pattern of seismicity observed in Figure 1, since it is so broad, cannot be used as evidence for a better location of the "Terwilliger Valley" earthquake. Either Wood's (1937) location or Gutenberg's (1943) revision would be consistent with the seismicity. The two locations are plotted in Figure 1. If Gutenberg's revision is more accurate, the earthquake would be associated with the main break of the San Jacinto fault but if Wood's location is correct, the 1937 earthquake would be associated with the high concentration of activity along the extended projection of the Coyote Creek fault. These possibilities seem equally likely.

An alternate explanation for the cluster of activity along the projection of the Coyote Creek fault is to postulate a shallow southwestward dip of the San Jacinto fault. Although the fault is near-vertical in dip on a regional scale, the dip does significantly depart from the vertical locally; as a matter of fact, it does so near the surface in the area in question (see Sharp, 1967). It seems unlikely that the San Jacinto fault maintains a shallow southwestward dip throughout the area of study. The cluster of 1966 foci between 4 and 7 km (Figure 4) might be related to a southwestward-dipping San Jacinto fault near its complicated branching with the Coyote Creek fault, but the squares do not delineate a simple fault plane. A near-vertical or very steeply dipping fault plane is judged most likely at depth for the San Jacinto fault.

Micro-earthquake activity recorded during the week following the May 21, 1967 ($M = 4.7$) earthquake suggests a close relation to that event. The Santa Rosa station (SR, Figure 2) recorded a micro-earthquake rate of about 90 events per day during the first day of operation of that array. Most of these events occurred in the zone of activity immediately northeast of the San Jacinto fault (see Figure 2 and solid symbols in Figures 3 and 4). Even though many of these events could not be located because they were clearly recorded on only 1 or 2 stations, their appearance on seismograms, especially their higher amplitudes and shorter S-P times at the Santa Rosa station, indicated that they were occurring nearly under that station. In contrast, during the 1966 array operation the micro-earthquake rate observed at Santa Rosa averaged less than 10 per day, and the seismograms indicated that the greatest activity was occurring in the cluster of events near Table Mountain (TM, Figure 1) at a depth of 4–10 km.

The above considerations suggest that the May 21st event was followed by a small series of aftershocks near the Santa Rosa station and indeed, that many of the events located in the week following that earthquake were aftershocks. Thus these events may indicate the approximate zone of energy release related to that earthquake. If so, the zone of energy release extended parallel to the San Jacinto fault a few km to the northeast and throughout a depth range of 3–15 km with possibly some energy release perpendicular to this zone near Table Mountain.

A count of micro-earthquakes recorded by Array #3 (operated for one week about a month after the May 21st event) gave a rate of approximately 6 events per day, which was less than half of that observed during the operation of Array #1 in 1966 and about one-third the level of activity recorded by a single trailer in the area during the earlier micro-earthquake survey of Brune and Allen (1967). Thus the aftershock activity associated with the May 21st earthquake had subsided three weeks later.

Observations outlined above point to a significant difference between the patterns of seismicity on the two sides of the San Jacinto fault. The different depths of activity might be correlated with the 1 to 2 mile (1.6 to 3.2 km) vertical rising of the southwest block found by Sharp (1967).

One of the interesting questions raised by the data is why does the activity stop at a depth of about 16 km? This may be related to creep phenomena occurring as a result of either an increase in temperature with depth, a change in composition, or a change from stable to unstable sliding as discussed by Scholz *et al.* (1969).

Many of the features of the seismicity of this region appear to be similar to that in the Cajon Pass area (Brune and Allen, 1967). That region is also a zone of complex fault branching and the epicenters occur in a complex distribution. However, there the deeper earthquakes (11 to 16 km) appear to be concentrated on the main San Andreas fault break, whereas the deeper earthquakes in this study are more broadly distributed.

McEvilly (1966) has pointed out that in central California at least two distinct types of earthquake sequences occur in association with magnitude 5 earthquakes. In one case the aftershocks are distributed over a broad zone of several tens of km (Udias, 1965) and in the other case the aftershocks are concentrated in a very small zone with dimensions of only a few km. Recently Eaton (1968) found the aftershocks of the Parkfield earthquake to be narrowly concentrated along a simple fault plane. Most of the earthquakes in our study do not appear to correspond to any of the above patterns. It is true that the 1967 activity tends to define a relatively restricted zone. Nevertheless, most of our data suggests a pattern of seismicity with more or less continuous complex activity. This seismicity occurs without definite association with a large earthquake and eludes any simple association with the planes of defined surface fault breaks. Although some of the scatter of hypocenters could be attributed to experimental errors, the accuracy of locations is sufficient to preclude the possibility that all the foci actually fall along 1 or 2 simple planar surfaces. Spot checks on the micro-earthquake activity in this region were made Jan. 29–30, 1968; July 30–Aug. 1, 1968; April 28–May 14, 1969; and Sept. 23, 1969. In all cases a continuing high rate of microearthquake activity—of the order of 10–30 events per day using the normalization of Brune and Allen (1967)—was indicated.*

Conclusions

(1) Accurate locations of 100 small earthquakes which occurred near the trifurcation of the San Jacinto fault show a complex distribution over a zone extending several km beyond the area outlined by the traces of faulting. There is no simple correlation between foci and planes of defined surface fault breaks.

(2) The earthquakes are limited to depths shallower than about 16 km. The patterns of seismicity observed on opposite sides of the San Jacinto fault are sig-

* Note added in proof: Another spot check was made during January 1970 and indicated a high rate of microearthquake activity.

nificantly different. A wide zone of activity occurs at a depth of 10–15 km on the northeast side of the fault; on the southwest side activity is shallower with a cluster of high seismicity occurring at a depth of 4–7 km along the northwestward projection of the Coyote Creek fault, several km northwest of the last traces of major surface faulting.

(3) A limited study of first motions indicates no systematic pattern; a wide variety of fault-plane orientations probably occurs.

(4) Most of the small earthquakes located in this study are not obvious aftershocks of any preceding large earthquake, but rather are representative of a more or less continuous complex pattern of seismicity with occasional larger events.

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References

Allen, C. R., P. St. Amand, C. F. Richter and J. M. Nordquist (1965). Relationship between seismicity and geologic structure in the Southern California Region, *Bull. Seism. Soc. Am.* **55**, 4, 753–797.

Allen, C. R. (ed.) (1967). Local Bulletin of Earthquakes in the Southern California Region, 1 January 1963 to 31 December 1966, Publication of the Seismological Laboratory, California Institute of Technology, 34 p.

Allen, C. R., J. N. Brune, J. M. Nordquist, C. F. Richter and V. Taylor (1968a). Local Bulletin of Earthquakes in the Southern California Region, 1 January 1967 to 31 December 1967, Publication of the Seismological Laboratory, California Institute of Technology, 16 p.

Allen, C. R., A. Grantz, J. N. Brune, M. M. Clark, R. V. Sharp, T. G. Theodore, E. W. Wolfe and M. Wyss (1968b). The Borrego Mountain, California Earthquake of 9 April 1968: A preliminary report, *Bull. Seism. Soc. Am.* **58,** 1183–1196.

Brune, James N. (1968). Seismic moment, seismicity, and rate of slip along major fault zones, *J. Geophys. Res.* **73,** 2, 777–784.

Brune, James N. and Clarence R. Allen (1967). A micro-earthquake survey of the San Andreas fault system in Southern California, *Bull. Seism. Soc. Am.* **57,** 2, 277–296.

Eaton, J. P. (1968). Spatial distribution of aftershocks of the June 27, 1966 Parkfield-Cholame earthquake in the San Andreas fault zone, Proc. of Conference on Geological Problems of San Andreas Fault System, edited by William R. Dickenson and Arthur Grantz, Stanford University Publications, Geological Sciences, Vol. XI, 84.

Flinn, E. A. (1960). Local earthquake location with an electronic computer, *Bull. Seism. Soc. Am.* **50,** 3, 467–470.

Gutenberg, Beno (1943). Earthquakes and structure in Southern California, *Bull. Geol. Soc. Am.* **34,** 499–426.

Lehner, Francis and Frank Press (1966). A mobile seismograph array, *Bull. Seism. Soc. Am.* **56,** 4, 889–897.

McEvilly, Thomas V. (1966). The earthquake sequence of November 1964 near Corralitos, California, *Bull. Seism. Soc. Am.* **56,** 3, 755–773.

McEvilly, T. V. and K. B. Casaday (1967). The earthquake sequence of September, 1965 near Antioch, California, *Bull. Seism. Soc. Am.* **57,** 1, 113–124.

Scholz, C. H., M. Wyss and S. W. Smith (1969). Seismic and aseismic slip on the San Andreas fault, *J. Geophys. Res.* **74,** 8, 2049–2069.

Sharp, Robert V. (1967). San Jacinto fault zone in the peninsular ranges of southern California, *Geol. Soc. Am. Bull.* **78,** 705–730.

Udias, Agustin (1965). A study of the after shocks and focal mechanism of the Salinas-Watsonville earthquakes of August 31 and September 14, 1963, *Bull. Seism. Soc. Am.* **55**, 1, 85–106.

Wood, Harry O. (1937). The Terwilliger Valley earthquake of March 25, 1937, *Bull. Seism. Soc. Am.* **27**, 4, 305–312.

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